Reprinted from the Journal of the American Ceramic Society, Vol. 66, No. 11, November 1983

A Modified Indentation Toughness Technique

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A modified indentation technique for measuring toughness is described. The method retains the elastic/plastic basis of previous contact fracture descriptions but eliminates explicit reference to residual stress parameters in the toughness formulation. Accordingly, improved correlations between indentation data and "conventional" K_c values are obtained, even for materials (e.g. anomalous glasses) with nonideal deformation responses.

INDENTATION methods are now widely used for determining toughness characteristics of brittle glasses and ceramics. These methods fall into two main categories: (1) tests in which K_c is evaluated from direct measurements of crack size as a function of indentation load[1,2] and (2) tests where the indentation crack serves as a controlled flaw in a flexural specimen, so that K_c is determined by a strength measurement.[3,4] Estimates of absolute accuracy levels run at 30 to 40% for both categories, for materials with "well-behaved" indentation patterns.[2,4]

A critical factor in any indentation toughness determination is a proper accounting of the residual contact stresses in the fracture mechanics formulas. These stresses play a primary role in driving the cracks at all stages of growth, both during and after the indentation cycle. Existing models of the fracture processes are based on oversimplistic elastic/plastic analyses,[5-7] necessitating the "calibration" of the residual field terms from "standard" materials of known toughness.[2,4] Implicit in all of these models are certain assumptions concerning the geometrical similitude of the indentation patterns from material to material. As shall be indicated, cases arise where such similarity principles are no longer applicable, leading to unacceptable error levels in the toughness estimates. In light of this problem, a "modified" indentation testing approach, a "hybrid" of the two methods categorized above, which avoids specific reference to residual stress terms altogether is proposed in this report.

To begin, the basis of the two existing methods is outlined. In the first (Fig. 1), the characteristic crack size, c_0, is measured, usually from surface radial traces, at given indentation load, P. Direct observation of the crack evolution during the actual contact process shows that the bulk of the surface growth occurs on unloading, i.e. as constraining elastic stresses are removed.[5] Under such conditions the crack approaches its immediate post-indentation configuration in a state of stable equilibrium. It may then be written[2]

$$K=\chi P/c_0^{3/2}=K_c \qquad (1)$$

where the parameter χ characterizes the intensity of the residual driving force, as the toughness equation. Strictly, measurements of c_0 after the event should be conducted in an inert environment, for the crack may be susceptible to further, subcritical extension in the persisting contact field.

In the second method, Fig. 1, the indentation crack is subjected to an applied stress, σ_a. The system remains in equilibrium in inert test environments, so that the stress intensity factor now becomes[6]

$$K=\chi P/c^{3/2}+\psi\sigma_a c^{1/2}=K_c \qquad (2)$$

where ψ is a crack-geometry parameter. This state of equilibrium is maintained by stable growth of the crack with increasing stress until failure occurs at the maximum in the $\sigma_a(c)$ function; thus, at $d\sigma_a/dc=0$, Eq. (2) gives

$$\sigma_m=3K_c/4\psi c_m^{1/2} \qquad (3a)$$

$$c_m=(4\chi P/K_c)^{2/3} \qquad (3b)$$

In this type of test the most accessible variables are P and σ_a, so c_m is usually eliminated from Eq. (3) to obtain[4]

$$(256\chi\psi^3/27)^{1/4}(\sigma_m P^{1/3})^{3/4}=K_c \qquad (4)$$

In this case toughness evaluations can be made without ever having to measure a crack dimension.

The usefulness of Eq. (2) or (4) for K_c determinations thus depends on the ability to specify the material dependence of the residual strain parameter, χ. For an ideal elastic/plastic material in which the indentation process can be represented by an "expanding cavity" model,[8] this dependence is relatively straightforward; $\chi \propto (E/H)^{1/2}$ is obtained approximately, where E is Young's modulus and H is hardness.[7] Embodied in this idealization is the assertion that the plastic component of the deformation is a constant volume, radial displacement process, characterized by a well-defined yield stress. Not all brittle materials deform in this way, however. So-called "anomalous" (network former) glasses and porous or phase-transforming ceramics can accommodate the indentation volume, at least partially, by structural densification. Such densification modes produce much lower residual stress levels in the constraining elastic material around the indentation, with consequent reductions in the appropriate χ values.[9] Similar reductions may be expected in softer ceramics which minimize elastic constraints by allowing yielded material to "pile up" around the penetrating indenter, as occurs in most metals.[10] Additional, post-indentation relaxation of the χ term may be effected by subcritical growth of lateral cracks,[4,11] mechanical removal of the contact deformation zone,[3] specimen heating,[12] etc.

In selecting standard materials for calibrating the toughness equations, candidates are sought for which the deformation response is close as possible to the ideal.[2,4] In general, such a calibration will provide an upper bound to χ for any subsequent test specimen. This in turn will tend to bias the indentation-determined toughness values above the "true" values. An extreme example of this is shown in Table I for soda-lime and borosilicate glasses, which are normal and anomalous, respectively, in their indentation behavior.[9] The K_c values from indentation[2,4] and "conventional" (double-cantilever beam)[13] determinations agree to within 25% for the normal glass, whereas differences greater than a factor of 2 are found for the anomalous glass. Discrepancies of this magnitude are hardly conducive to comparative materials evaluation.

It is clear from this discussion that the indentation approach will benefit by any modification which minimizes reliance on the χ parameter. Reference to Eq. (3) shows that such reliance can be eliminated altogether if P is replaced by c_m as a test variable; the new toughness equation then follows directly from Eq. (3a)

$$(4\psi/3)\sigma_m c_m^{1/2}=K_c \qquad (5)$$

The modified procedure represents a hybrid of the two earlier methods, in that both a crack size and a strength measurement are required. Of course, the fact that χ does not appear explicitly in Eq. (5) does not mean that residual stresses play an insignificant role in the indentation test; χ is simply incorporated into a directly measurable quantity via Eq. (3b).

It is possible to measure c_m directly by setting up a microscope facility onto the strength test apparatus and monitoring the crack extension to the failure point.[6,14] However, this is not a practical arrangement for most routine materials testing laboratories. An alternative procedure is to use "dummy" indentations, as in Fig. 2.[15] Thus, more than one (three, in the present tests) Vickers indentations are placed on the prospective tensile surface, within the inner span, of a 4-point bend specimen. Ostensibly, all such indentations should experience a near-identical stress history during the bend test, provided the separations are

CONTRIBUTING EDITOR — A. G. EVANS

Received June 22, 1983; approved July 15, 1983.
Supported by the Office of Naval Research, Metallurgy, and Ceramics Program.
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*On leave from the University of New South Wales.

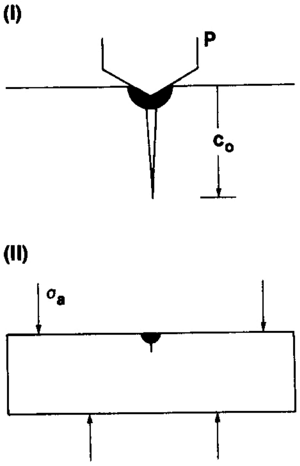

Fig. 1. Schematics of established indentation methods, (*I*) direct crack size method and (*II*) controlled flaw/strength method.

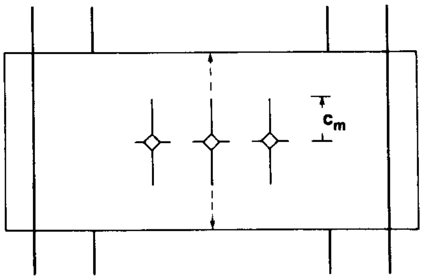

Fig. 2. "Dummy" indentation method. Specimen breaks from one indentation, leaving survivors on surface from which c_m can be measured.

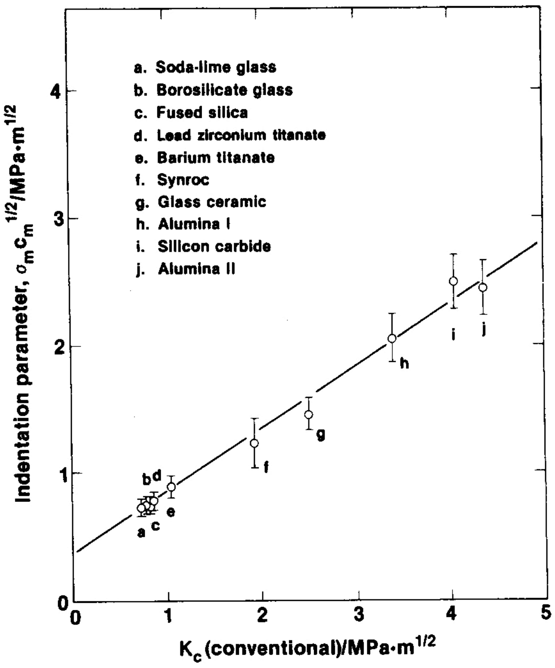

Fig. 3. Results of tests using modified indentation toughness method for selected glasses and ceramics. ((*a*, *b*, *c*) From Schott-Ruhrglas (GmbH), W. Germany; (*d*) Plessey Industries, Sydney, Australia; (*e*) Channel Industries, Inc., Santa Barbara CA; (*f*) synroc B, Australian Atomic Energy Establishment; (*g*) Pyroceram, Code 9606, Corning Glass Works, Corning, NY; (*h*) AD 96, Coors Porcelain Co., Golden, CO; (*i*) NC203, Norton Co., Worcester, MA; (*j*) F99, Freidrichsfeld GmbH, Mannheim, W. Germany.)

Table I. Evaluations of K_c for Glasses by Conventional and Indentation Techniques

	K_c (MPa·m$^{1/2}$)		
Glass	Double-cantilever beam	Indentation I*	Indentation II*
Soda-lime (normal)	0.75	0.8	1.0
Borosilicate (anomalous)	0.77	1.6	1.2

sufficiently large that interactions with neighbors do not occur. In practice, the inevitability of slight inhomogeneities in the loading system ensures that failure occurs from just one of the indentations, leaving intact dummies available for the measurement of the critical crack dimensions.

The results of tests using the modified procedure are shown as a plot of $\sigma_m c_m^{1/2}$ against K_c for several materials in Fig. 3. The vertical error bar on each data point represents standard deviation bounds for measurements on 12 to 15 specimens. The data cannot be fitted to a straight line through the origin, as required by Eq. (5), implying that the crack-geometry parameter, ψ, does not satisfy the similitude requirements. Nevertheless, a linear best fit

$$K_c = A\sigma_m c_m^{1/2} + B \qquad (6)$$

with $A = 2.02$ and $B = -0.68$ MPa·m$^{1/2}$ does intersect all error bars and should, therefore, serve as a convenient empirical calibration function for evaluating the toughness of other materials. Moreover, the data points for the soda-lime and borosilicate glasses now fall almost identically on the representative line, so the gross departures from universal indentation behavior evident in Table I do indeed appear to have been largely eliminated.

In weighing up the merits of the present technique, any attendant disadvantages must be considered; P has been replaced with c_m as a test variable, and crack dimensions are notoriously susceptible to measurement errors (particularly on the small scale of typical indentation patterns). Recall from the derivation of Eq. (3) that the failure condition is approached via a maximum in the $\sigma_a(c)$ function, so small variations in stress levels on the dummy indentations could lead to substantial variations in crack sizes. It is therefore important to adopt a consistent experimental methodology in the calibration scheme of Fig. 3 to minimize the influence of any systematic component in such variations.

Accordingly, the modified indentation method should be seen as supplementing rather than replacing its predecessors. It is certainly to be preferred for any material suspected of deforming by other than constrained plastic flow. It might also be used effectively in instances where stress relaxation processes can occur, e.g. at elevated temperatures. The relative length of the crack arms perpendicular and parallel to the tensile direction in Fig. 2 then provide an immediate indication of the intensity of the residual stress influence. If the former arms show no signs of having expanded during the strength test, it can be assumed that the residual field is no longer a dominant force in the fracture mechanics determinations.

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